Semrock Technical Note Series:

A New Class of Polarization Optics Designed Specifically for Lasers

Semrock a Unit of IDEX

The Standard in Optical Filters for Biotech & Analytical Instrumentation

A New Class of Polarization Optics Designed Specifically for Lasers

1. Introduction

In optical systems often it is necessary to isolate a single state of polarization of light. Many interferometric and spectroscopic systems are sensitive to polarization. Polarization can even play a role in laser-based cutting, for example, in which the shape of the cutting region becomes highly anisotropic when polarized light is used. Linear and even circular polarization can be obtained using a “polarizer,” or a component that transmits a single state of polarization while absorbing, reflecting, or deviating light with the orthogonal state of polarization. Optical applications that depend on good polarization control include laser materials processing, polarization diversity detection in communications and rangefinding, liquid crystal device characterization and manufacturing, fluorescence polarization assays and imaging, second-harmonic-generation imaging, polarized Raman spectroscopy, and a wide variety of laboratory laser applications based on holography, interferometry, etc., to name a few.

There are many types of polarizers and polarizing beamsplitters available, but none of them solves every problem. There are important applications for which there is still no ideal polarization component. This article compares the strengths and weaknesses of some of the most popular component solutions on the market today, and then explains how Semrock’s advanced optical filter technology is being applied to a new class of polarization components designed specifically for lasers. This new class of filters is filling some key gaps in the polarization component market.

2. Myriad polarization components

A perfect polarizer exhibits 100% transmission of the desired state of polarization and complete extinction of the undesired state. Often the most important parameter that describes a real polarizer is the “contrast ratio,” or the ratio of the transmission through a pair of identical aligned polarizers to the transmission through the same pair of crossed polarizers. (The “extinction ratio” is the inverse of the contrast ratio.) Contrast ratios typically vary from about 100:1 to as large as 100,000:1.

Probably the most well-known type of polarizer is the polymer sheet polarizer, based on the original “H-Sheet” invented by E.H. Land of Polaroid fame in 1938. These are a type of “absorbing polarizer,” which eliminates the undesired polarization via absorption, as opposed to reflection. Polymer sheet polarizers – including versions with the sheets sandwiched between glass plates – are a good solution for lower-end applications, like polarized sunglasses, but they suffer from low contrast, low transmission, and low optical damage thresholds.

Glass film polarizers are a newer, higher-performance type of absorbing polarizer in which asymmetric silver nanoparticles are embedded in a thick soda-lime glass film that is sandwiched between two glass substrates (see Figure 1, top left). The nanoparticles selectively absorb one orientation of linearly polarized light more strongly than the other, resulting in very high contrast performance. They also offer larger apertures and good optical quality, but the transmission of these and all absorbing polarizers tends to be fairly poor, and they cannot withstand very high optical intensities.

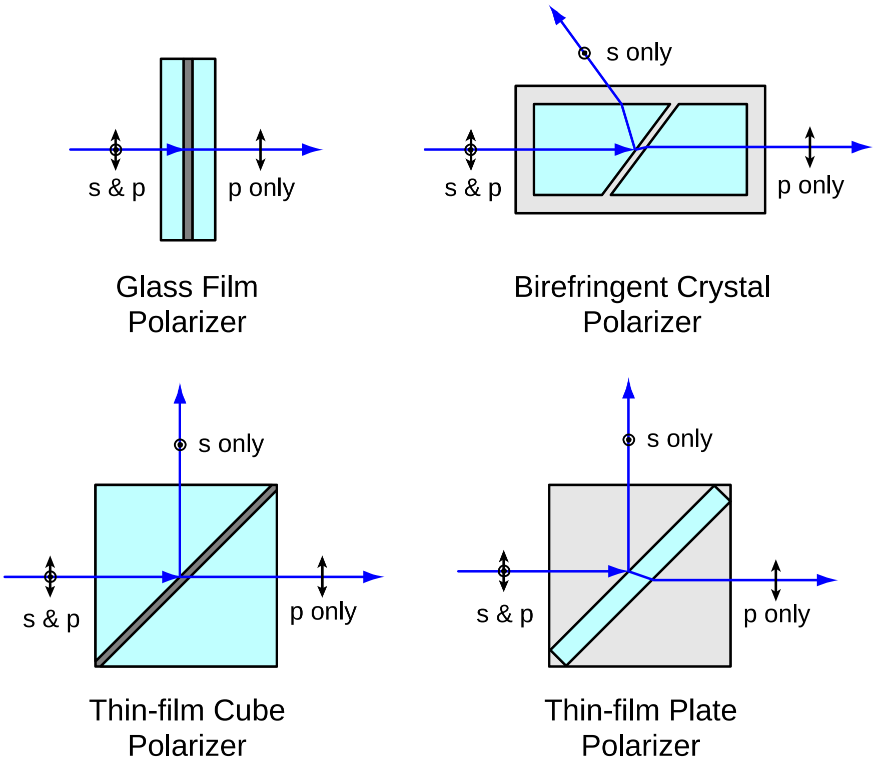
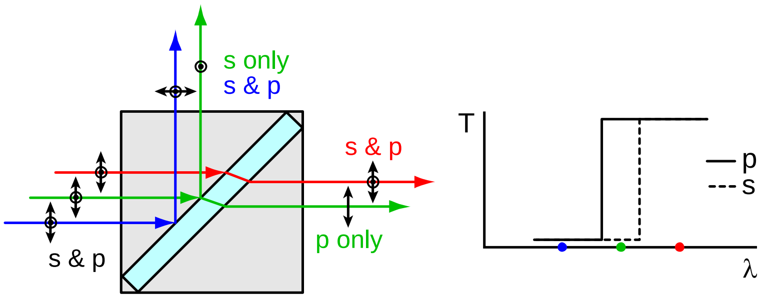


Figure 1: Examples of some of the main types of polarizers and polarizing beamsplitters.

In birefringent crystal polarizers (see Figure 1, top right) different polarizations of light rays incident on an interface at an oblique angle are deviated by different amounts. Light is incident at certain angles on the two interfaces formed by a gap between two birefringent crystals, such that these angles are near or equivalent to Brewster's angle for "p" polarized light, which is therefore nearly completely transmitted, whereas at these angles "s" polarized light is totally internally reflected. For example, in "Glan" Calcite polarizers, extinction is achieved by total internal reflection of s-polarized light at a crystal-air gap (Glan-laser) or crystal-epoxy gap (Glan-Thompson). Birefringent crystal polarizers achieve high contrast ratios, high transmission, and high optical damage thresholds. However, main drawbacks include a limited aperture size due to the high cost of growing good optical quality crystals, and they are not well suited for precise laser delivery and imaging applications – they are very thick, and thus prone to optical wavefront distortion, scattering, and beam deviation that causes walk during rotation.

Conventional optical thin-film polarizers achieve discrimination through interference in a dielectric optical thin-film coating. These filters generally operate near the edge of a “stopband” region of high reflection (as results from a quarter-wave stack of layers, or a nearly quarter-wave stack of layers). When light is incident on such a coating at a non-normal angle of incidence, the width of the stopband for “p” polarized light becomes narrower than the width of the stopband at normal incidence, while the width of the band for “s” polarized light becomes wider, such that the edge “splits” and there is a narrow range of wavelengths for which there is high-transmission of “p” polarized light (just outside the stopband for “p”) but high reflection (attenuation) of “s” polarized light (just inside the stopband for “s”). Such coatings can be applied to the hypotenuse of a right-angle prism which is combined with a second such prism to create a cube-shaped component (so-called “cube beamsplitter polarizers”), or to a single substrate (so-called “plate polarizers”).



Thin-film Plate Polarizer

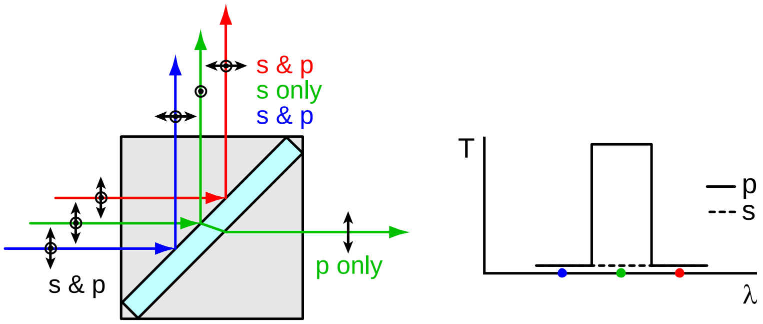
Figure 2: Shows how different wavelengths of light are selectively transmitted and reflected by a thin-film plate (or prism) polarizer.

The basic principle of a thin-film polarizer is illustrated in Figure 2. Notice that typically thin-film polarizers operate only over a particular wavelength range – for wavelengths shorter than this range both polarizations are reflected, while for wavelengths longer than this range both polarizations are transmitted. Thin-film cemented or air-spaced prism-cube polarizers and thin-film plate polarizers both offer larger apertures and good optical quality, so they work well for precise laser delivery systems and for imaging, but a main drawback is that the contrast is generally low.

3. Something new under the sun? Semrock polarizers are unique.

Semrock has developed new polarization components based on the thin-film plate polarizer geometry. Like all thin-film plate polarizers, Semrock’s polarizers offer excellent performance in terms of high transmission and optical quality, high reliability and laser damage thresholds, and large apertures. But now these fundamental advantages have been married with Semrock's ability to deposit many hundreds of thin-film coating layers with high precision using ion-beam sputtering – widely considered to be the highest-quality thin-film coating technology. The result is breakthrough improvements in performance. Foremost among these is contrast – Semrock's polarizers are guaranteed to achieve higher than 1,000,000-to-1 contrast (extinction less than 10^{-6}), rivaled only by the low-transmission, low-optical-damage-threshold glass-film polarizers. And because of the steep edges and sharp spectral features achieved by thin-film coatings with many hundreds of precisely deposited layers, Semrock can also maximize the wavelength ranges over which these polarizers function, thus addressing the other key limitation of thin-film plate polarizers.

Perhaps the most unique Semrock polarization component is the *polarizing bandpass filter*. Like the name suggests, this component is a highly efficient polarizer and a bandpass filter in a single component. Both functions come from the coatings on a single glass substrate – it is not two components packaged in a single "box." More specifically the polarizing bandpass filter is an optical thin-film filter that operates at an oblique angle of incidence and exhibits high transmission of light with "p" polarization and simultaneously deep attenuation of light with "s" polarization within a certain wavelength range (the passband), with a p-to-s polarization contrast ratio better than 10^6:1. Outside of the passband, the filter exhibits deep blocking – better than optical density (OD) 6 – for light of all states of polarization. Therefore, the filter is effectively a bandpass filter for "p" polarization and a broadband blocking filter for "s" polarization.



Polarizing Bandpass Filter

Figure 3: Shows how different wavelengths of light are selectively transmitted and reflected by a polarizing bandpass filter. Note that all polarization states of light outside the passband are blocked.

The principle of operation of the polarizing bandpass filter is shown in Figure 3. Comparing this figure to Fig. 2, we observe a key difference is that only light of the desired polarization is transmitted through the filter, whereas for a conventional thin-film plate polarizer light of the undesired polarization is transmitted at wavelengths slightly longer than the operating range (red ray in Fig. 2). Also, what is not apparent from this simplified diagram is that the operating range itself (the passband of the filter) can be substantially broader for the polarizing bandpass filter than that of a comparable thin-film plate polarizer. A broader operating range enables a wider range of laser or incoherent wavelengths, and also allows a very wide angular acceptance angle for a given wavelength within the passband.

Figure 4 shows the measured transmission for both p-polarized (solid blue curve) and s-polarized (dashed red curve) light through a polarizing bandpass filter designed for use with 532 nm laser light. This filter has a passband width of about 30 nm, and an angular acceptance range of 45 ± 7º at 532 nm. It achieves exceptionally high transmission for p-polarized light, has excellent optical quality (imaging-quality, with low scatter, wavefront distortion, and beam deviation), and the durability and high laser damage threshold expected from a high-performance laser-grade optic. But perhaps most remarkable is that contrast measured with crossed polarizers is guaranteed to exceed 1,000,000-to-1. In other words, the s-polarized light within the passband is blocked with optical density (OD) > 6. Blocking outside the passband for both polarizations also exceeds OD 6 in the visible wavelength range, and the filter has at least OD 2 blocking from the UV all the way up to 1100 nm (the full Si-detector sensitivity range).

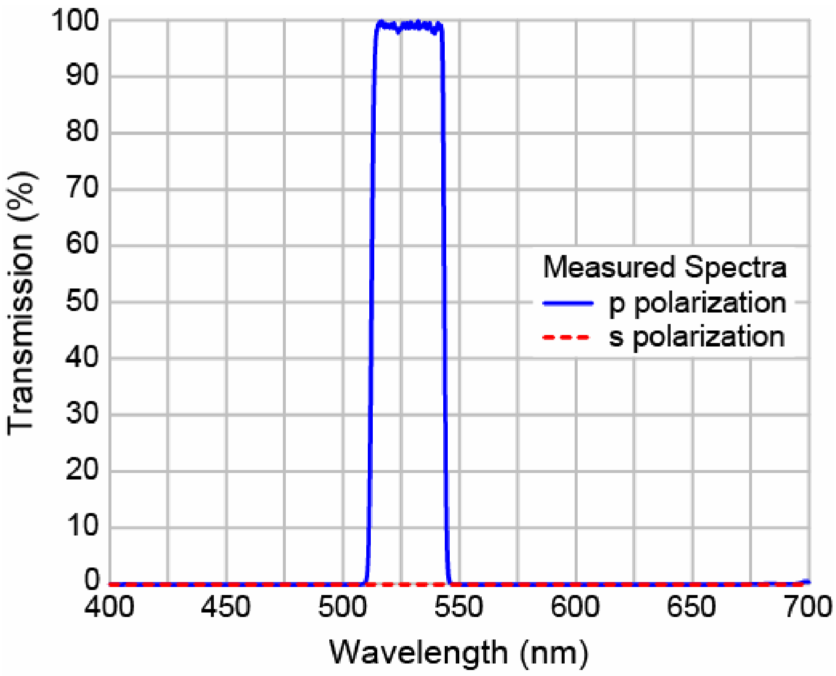


Figure 4: Example of the spectral performance of a polarizing bandpass filter. Actual measured data is shown for a filter designed to operate at or near 532 nm.

4. Semrock polarization filters compared to other polarization components

Table 1 contains a qualitative summary of the relative performance of different types of polarizers and polarizing beamsplitters in terms of their key performance metrics. The conventional components have well-understood strengths and weaknesses, making each suitable for some applications but not necessarily for others.

Table 1: Relative comparison of major types of polarizers and polarizing beamsplitters (listed in the left-hand column) in terms of key performance parameters (listed across the top row). Leading performance is highlighted in blue, while disadvantageous features are highlighted in red.

	Contrast	Transmission	Wavelength Range	Angle Tolerance	Laser Damage Threshold	Beam Deviation	Reliability	Aperture Size	Spectral Functionality	Beamsplitter Functionality
Glass Film Polarizers	**very high**	moderate	moderate	high	**low**	OK	OK	**large**		**no**
Wire Grid Polarizers	**low**	moderate	high	high	high	OK	**good**	**large**		**yes (90º)**
Glan Laser Polarizer	high	high	**very high**	**low**	**very high**	OK	OK	**small**		yes (not 90º)
Glan Thompson Polarizer	high	high	**very high**	moderate	moderate	OK	OK	**small**		**no**
Wollaston Polarizer	high	high	**very high**	moderate	moderate	OK	OK	**small**		yes (not 90º)
Broadband Thin-film Cube Polarizer	moderate	**very high**	high	high	high	**poor**	OK	moderate		**yes (90º)**
Laser Thin-film Cube Polarizer	moderate	**very high**	**low**	high	**very high**	**poor**	**good**	moderate		**yes (90º)**
Thin-film Plate Polarizer	moderate	**very high**	**low**	moderate	**very high**	OK	**good**	**large**		**yes (90º)**
Semrock Polarizing Bandpass Filter	**very high**	**very high**	**low**	moderate	**very high**	**good**	**good**	**large**	**unique!**	**yes (90º)**

Thin-film plate polarizers generally have a number of unique advantages relative to other types of polarizers. They can achieve the highest transmission of any polarizer. They can exhibit the best optical quality in terms of low scattering and wavefront distortion and negligible beam deviation (a critical parameter for polarizers due to beam walk during rotation). They can be made with excellent environmental reliability and the highest laser damage thresholds. Thin-film plate polarizer aperture sizes can be quite large (inches). And they naturally function as a beamsplitter with a 90º beam deviation of the blocked polarization.

Unlike birefringent crystal polarizers, thin-film plate polarizers tend to have a strong wavelength dependence since they operate on the principle of multiwave interference. Because they function over only a range of wavelengths, they are best suited for laser applications or for systems that limit signal light to a band of wavelengths. Glass film polarizers also have a limited wavelength range, though not as limited as thin-film plate polarizers.

However, birefringent crystal polarizers tend to be very limited in aperture size due to the high cost of growing good optical-quality crystals, and because they can also distort, scatter, and deviate the optical beam, they are not well suited for imaging applications. The main limitations of glass film polarizers and other absorptive polarizers are low transmission of the desired light and low optical damage threshold, making them unsuitable for many laser applications.

Semrock's ion beam sputtering technology has enabled breakthrough improvements to the performance of traditional thin-film plate polarizers. Foremost among these is contrast – Semrock polarizers are guaranteed to achieve higher than 1,000,000:1 contrast, rivaled only by the lower-transmission and low optical damage-threshold glass film polarizers. And, only Semrock polarizers can achieve unique spectral performance like the polarizing bandpass filters.

5. Applications for polarizing bandpass filters

What makes these filters unique is that they combine a polarizer and a bandpass filter together into one, single-substrate component. Linear polarization with a contrast ratio better than 10^6:1 is realized over a desired wavelength range (the passband), outside of which the filter has deep attenuation better than OD 6 for both polarizations. Such a unique spectral property, which, to the best of our knowledge, has not been realized before, has a variety of applications, all of which benefit from reduced optomechanical system complexity, higher overall transmission, decreased system weight, and, as a result, lower overall cost.

Some specific examples of applications and systems include:

- A complete laser clean-up filter which passes a single, desired polarization output from a laser at the desired laser wavelength while blocking both light at the laser wavelength of the orthogonal polarization as well as light of all polarization states at wavelengths adjacent to the laser line. All of the blocked light is considered "noise" in systems based on such lasers, and the better these noise sources can be blocked, the better the signal-to-noise ratio of the system.

- A laser communication detection system, designed to receive a laser signal of a single polarization, in which it is necessary to block all light at wavelengths other than the laser wavelength (especially the ambient light from the sun and other sources), as well as the undesired orthogonally polarized light at the laser wavelength; in such systems the large ratio between filter transmission and blocking, as well as the high polarization contrast ratio, lead directly to improved signal-to-noise ratio of the communication system.

- A harmonic-generation imaging system used for material characterization or biological research. For example, in second-harmonic-generation (SHG) microscopy for biological imaging a laser is used to illuminate the sample of interest (e.g., at around 810 nm), and the microscope collects and images the SHG light at one half of the illumination wavelength (e.g., at around 405 nm). The efficiency of the SHG process as well as the polarization dependence can be used to determine unique characteristics of the biological material not easily measurable with standard or even fluorescence microscopy. High-fidelity images require good isolation of the frequency-doubled wavelength as well as good polarization extinction from a component that does not distort the high-quality imaging path.

- A fluorescence detection system which measures the degree of polarization of the fluorescence emission, thus indicating whether or not one species binds to another species with a fluorescent label attached. The principle behind such systems is based on a polarized excitation source exciting a certain orientation (dipole moment) of the fluorescent molecules so that ideally they would also emit polarized fluorescence, except they are very quickly depolarized due to motion. However, when another species binds to the labeled target, the target becomes much less mobile so that the degree of polarization of the emitted light increases. Even more information can be obtained by measuring the degree of polarization as a function of time. This technique is used in both high-speed fluorescence detection (e.g., microplate readers) as well as in fluorescence microscopy.

- A simultaneous polarization and wavelength multiplexing system. For high-power laser applications such as laser cutting and machining, one of the important challenges is power scaling of the laser – obtaining higher and higher total power without sacrificing brightness (which is the power per unit area, per unit wavelength interval, per unit beam solid angle). One way to increase brightness is to combine many laser beams together, each with a slightly different wavelength (so-called “wavelength multiplexing”), and using two orthogonal polarizations at each wavelength (so-called “polarization multiplexing”). Polarizing bandpass filters are ideally suited for achieving simultaneous polarization and wavelength multiplexing.

6. Concluding remarks

While there are a number of mature polarizer technologies that have been on the market for a long time, none of them solves every polarization problem. By applying advanced ion-beam sputtering optical filter technology to polarization control, Semrock is now able to make polarizers and polarizing beamsplitters that achieve exceptionally high contrast (> 1,000,000:1), excellent image-quality transmission, high laser damage threshold and environmental reliability, and availability in larger sizes for larger beams. And this same technology is being applied to other novel polarization components, such as multi-wavelength thin-film plate polarizers that will cover the fundamental and primary harmonics of a Nd:YAG laser in a single component.

7. References

[1] "Understanding Polarization," Semrock White Paper Series, www.semrock.com.

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